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Engineering Design File

Hydrologic Modeling of Final Cover (60% Design Component)

INEEL
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5. Summary:

The long-term infiltration rates through the proposed landfill cover section for the INEEL CERCLA Disposal Facility (ICDF) were estimated to determine percolation from the base of the cover. Hydrologic modeling was conducted to simulate extreme climatic scenarios that could result in infiltration through the cover. Climatic parameters used during hydrologic modeling were based on site data from 10 years representing average conditions (1967 to 1976) followed by four years with precipitation greater than the 90th percentile of recorded annual precipitation (1957, 1963, 1964, and 1995) to represent an extreme climatic scenario. The modeling effort evaluated the performance of the cover by determining surface runoff, infiltration through the upper soil component of the cover system, lateral drainage, and cover defects. The performance of the soil cover was evaluated based on the water flux at a node located at the base of the ICDF landfill cover. Sensitivity analyses were performed to determine the optimum water storage layer thickness and upper precipitation bound.

Based on the results from the simulations reported in this Engineering Design File for the ICDF landfill cover, results from experimental studies at the INEEL, and experimental and modeling results from other sites in the western United States, it is believed that the cover design proposed for the ICDF landfill represents a state-of-the-practice design for a landfill cover that minimizes infiltration into the waste. Any leakage that occurs through the cover is likely to be intercepted by the lateral drainage layers at the base of the cover. A conservative estimate of 0.1 mm/year of percolation from the base of the cover was determined based on the estimated breakthrough from the upper section of the cover. Based on the results reported in this Engineering Design File, it is believed that the cover design, which incorporates a store and release soil cover underlain by a capillary break and composite liner system, represents the best technology for minimizing infiltration into the landfill given site-specific climatic conditions.

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ABSTRACT

The long-term infiltration rates through the proposed landfill cover section for the INEEL CERCLA Disposal Facility (ICDF) were estimated to determine percolation from the base of the cover. Hydrologic modeling was conducted to simulate extreme climatic scenarios that could result in infiltration through the cover. Climatic parameters used during hydrologic modeling were based on site data from 10 years representing average conditions (1967 to 1976) followed by four years with precipitation greater than the 90th percentile of recorded annual precipitation (1957, 1963, 1964, and 1995) to represent an extreme climatic scenario. The modeling effort evaluated the performance of the cover by determining surface runoff, infiltration through the upper soil component of the cover system, lateral drainage, and cover defects. The performance of the soil cover was evaluated based on the water flux at a node located at the base of the ICDF landfill cover. Sensitivity analyses were performed to determine the optimum water storage layer thickness and upper precipitation bound.

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Appendix E—Sensitivity Analysis

ACRONYMS

AMC	antecedent moisture condition
ARAR	applicable or relevant and appropriate requirements
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFA	Central Facilities Area
CCL	compacted clay liner
cm/sec	centimeters per second
CN	curve number
EDF	Engineering Design File
EBTF	Engineered Barriers Test Facility
ICDF	INEEL CERCLA Disposal Facility
IDAPA	Idaho Administration Procedures Act
INEEL	Idaho National Engineering and Environmental Laboratory
km/hr	kilometers per hour
KPa	Kilopascals
m	meters
mm/day	millimeters per day
mm/year	millimeters per year
NOAA	National Oceanographic and Atmospheric Administration
RAO	remedial action objectives
RCRA	Resource Conservation Recovery Act
SCS	Soil Conservation Service
SWCC	soil water characteristic curve
WGEN	Weather Generation Program

Hydrologic Modeling of Final Cover (60% Design Component)

1. INTRODUCTION

The INEEL CERCLA Disposal Facility (ICDF) landfill will be capped with a robust state-of-the practice cover to minimize long-term infiltration. The cover system must meet the remedial action objectives (RAOs) to minimize infiltration and maximize run-off and protect against inadvertent intrusion for greater than 1,000 years (DOE-ID 1999). The cover system must also meet applicable or relevant and appropriate requirements (ARARs) under the Idaho Administration Procedures Act (IDAPA) and Resource Conservation and Recovery Act (RCRA) Subtitle C requirements for closure of a hazardous waste landfill.

The cover system will minimize infiltration and maximize run-off by maintaining a sloped surface, storing water for latter release to the atmosphere, lateral drainage, and providing a low permeability composite liner barrier system. The cover can be divided by function into three main sections. Each section and its function are listed below:

- Upper section: The upper water storage component provides water storage during wet periods for latter release into the atmosphere during dry periods
- Middle section: The biointrusion provides protection from burrowing animals and a capillary break
- Lower section: The lower section includes a composite liner system that has a permeability less than or equal to the permeability of the landfill bottom liner system that complies with IDAPA 58.01.05.008 (Code of Federal Regulation [CFR] Part 264.310). Lateral drainage can occur above the composite liner system through a high permeability drainage material.

Each component in the cover profile is shown in Figure 1-1.

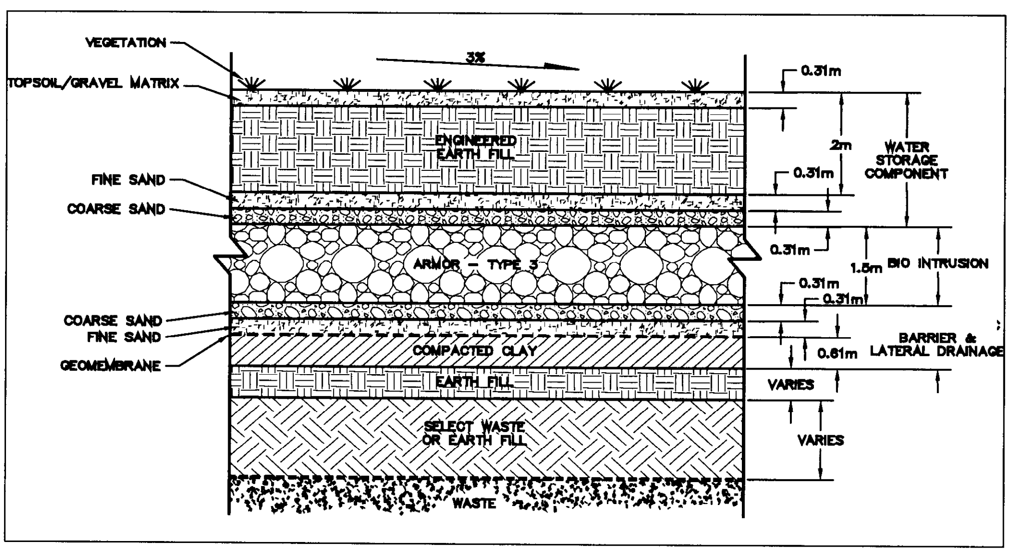

Figure 1-1. Schematic of modeled cover section.

The current hydrologic model showed that the upper and middle landfill cover sections alone were effective in reducing the infiltration. Using conservative estimates of long-term base and extreme cases of climatological conditions and a flat landfill cover surface, the model predicted that 0.37 and 0.49 millimeters (mm) average annual infiltration, respectively could occur in the long term (DOE-ID 2001a). Since the cover will be sloped, infiltration will be further reduced due to surface water run-off. Moreover, drainage from the upper and middle sections will be intercepted by the lower landfill cover composite liner system and diverted through the lateral drainage layer.

The purpose of this study is three-fold. First, expand the current hydrologic model to include the lower section of the cover and the two-dimensional (e.g., vertical and lateral) drainage paths to determine the ultimate long-term percolation from the base of the compacted clay liner (CCL) and into the waste mass. Second, determine the increase in infiltration due to cover defects (e.g., burrowing animals and silt migration clogging drain layers). Third, evaluate the sensitivity of the upper landfill cover section to optimize the water storage layer thickness and provide an upper bound of precipitation to determine the effectiveness of the upper section for storing large volumes of water without breakthrough into the underlying cover sections.

2. METHODS

Methods used for hydrologic modeling include a combination of an unsaturated flow model for determining the upper cover section infiltration and analytical solutions for determining surface water run-off, lateral drainage, and infiltration due to cover defects. One-dimensional flow through the upper section was determined using the unsaturated hydrologic model SoilCover™ 2000, Version 5, developed by the University of Saskatchewan (Geo-Analysis 2000). Surface water run-off from the sloped cover surface was determined using the curve number method developed by the U.S. Soil Conservation Service (SCS) (Soil Conservation Service 1972). Lateral drainage was determined using Dupuit unconfined groundwater flow equations (Fetter 1994).

Figure 2-1 shows the overall cover system model configuration. The arrows in Figure 2-1 represent the layers that were evaluated to determine the ultimate percolation from the base of the Soil Bentonite Liner, Point F. The layers are represented by observation points and are referenced throughout this Engineering Design File (EDF) to provide a point of reference for the analyses. Each point is described below:

- Point A: Precipitation on the cover surface
- Point B: Evapotransporation from the cover surface
- Point C: Surface water run-off from the cover surface
- Point D: Breakthrough from the base of the water storage layer
- Point E: Lateral drainage
- Point F: Percolation from the base of the soil bentonite liner.

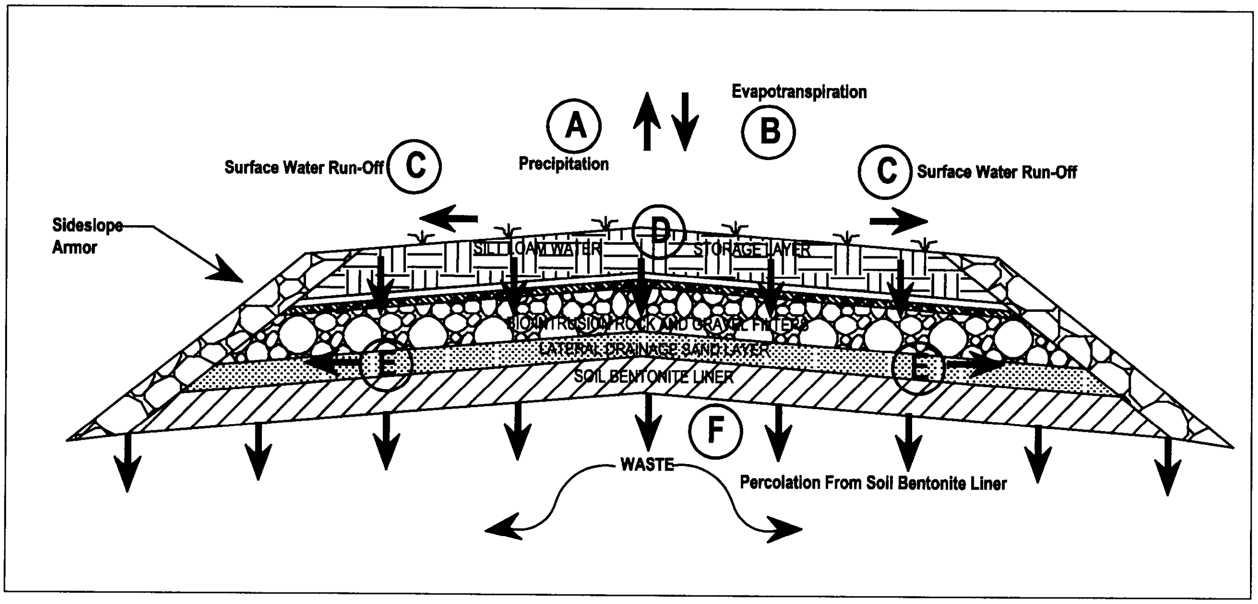

Figure 2-1. Hydrologic model geometry and location of observation points.

For purposes of the analyses, it was assumed that the flexible membrane liner and other synthetic materials overlying the CCL deteriorate in the long term leaving only the earthen materials in the cover to reduce infiltration. The results from the analytical solutions and unsaturated flow model were also combined on a daily basis and reported as an average annual value. A detailed description of the unsaturated flow computer program SoilCover™ 2000 and the description of the model geometry are provided in Appendix A.

3. INPUT DATA

3.1 Climatological Data

The ICDF landfill cover will be subjected to long-term climatological conditions including:

- Ambient air temperature
- Net radiation
- Relative humidity
- Wind
- Precipitation.

Selection of representative conservative weather data sets to be used for the overall hydrologic model was based on annual precipitation. Previous hydrologic modeling of the final cover evaluated two climate scenarios that included a 10-year period having the conditions that most likely would break through the upper section at Point D shown in Figure 2-1 and an extreme condition to address potential long-term climate changes. The extreme condition included back-to-back years that had precipitation amounts greater than the 90th percentile. Figure 3-1 shows the period of climate data and the selected 10-year base case period. The 10-year period selected was from October 1, 1967, through September 30, 1976, with an average annual precipitation of 237 mm. This period provides the most likely chance of cover breakthrough from the upper section since the 10-year average annual precipitation (237 mm) is greater than the average annual precipitation (218 mm) for the period of record. Moreover, the selected 10-year period includes higher-than-normal precipitation events during the initial years that "load" the water storage cover layer with moisture, allowing the model to simulate the cover's recovery capability after large precipitation events.

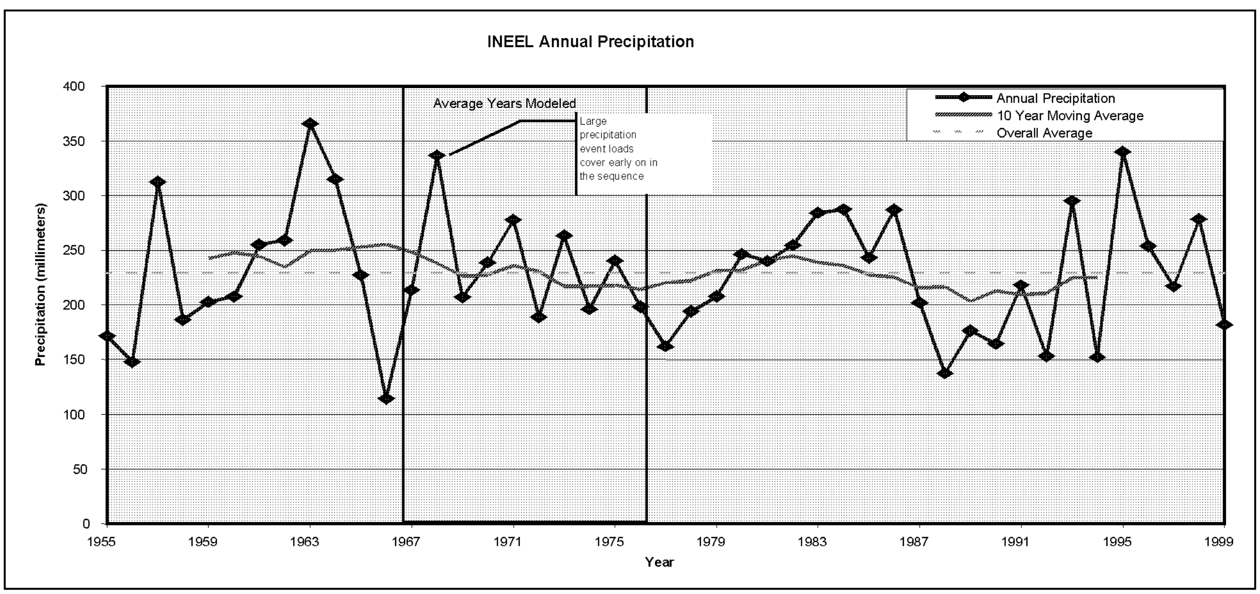

Figure 3-1. INEEL annual precipitation.

Figure 3-2 shows the years selected for the extreme scenario. The 90th percentile for the period of record was 306 mm per year. The years with precipitation greater than the 90th percentile were 1957, 1963, 1964, 1968, and 1995 as shown in Figure 3-2. These years back-to-back (with the exception of 1968, which was included in the average climatic scenario) were used to determine breakthrough from the upper section for long-term, worst-case climate conditions.

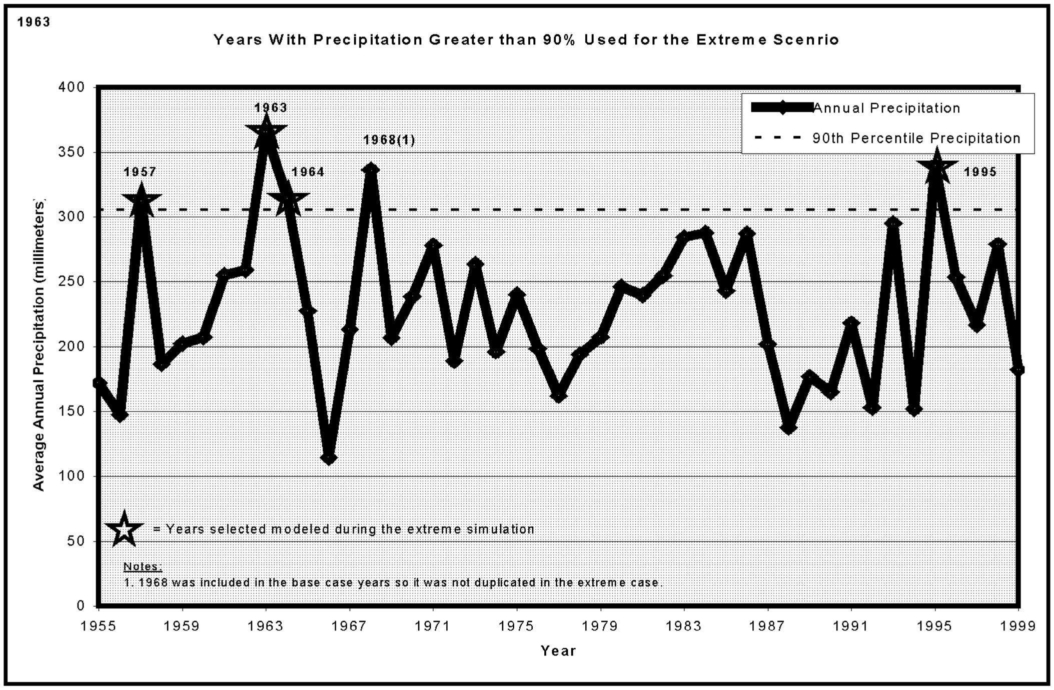

Figure 3-2. Extreme precipitation events.

Maximum and minimum daily temperatures for the simulated years were included in the input data sets for the unsaturated flow model, SoilCover 2000. Daily precipitation, maximum and minimum relative humidity, and wind speed data from these years were also input to the model. As a result of the lack of relative humidity data for the years simulated (only two years of data were available), monthly averages for minimum and maximum relative humidity were used in the model.

Global solar radiation data were synthetically generated using the Weather Generating Program (WGEN) computer code, which takes into account observed precipitation and temperature data (Martian 1995). These data were converted to net radiation using the method provided in the Handbook of Hydrology (Maidment 1993). The calculations and assumptions used are shown in Appendix B. This conversion required the mean daily temperature, mean daily vapor pressure, and the latitude of the site. The daily weather data used in the simulations are provided in Table 1-1 in Appendix B.

The climatological data for the extreme case was used in this study to determine the worst-case percolation through the base of the cover. Additionally, typical storms for Idaho Falls are of short duration (i.e., less than six hours) with high intensity resulting in run-off with little time for infiltration. Storm events for the hydrologic cover model were distributed over 12 hours, maximizing infiltration.

3.2 Snow Pack and Vegetation

The winter snow pack was determined from weather information gathered at the site. Average snow pack and snow melt dates from 1970 to 2000 were used in the model. For the years modeled, the snow pack was entered as rain during the runoff period. Table 3-2, Snow Pack Information, shows the dates used for each period. The analysis assumed that all the water generated from melting snow infiltrates into the water storage layer. The annual quantities of melted water from the snow pack that are available for infiltration are included in Appendix B.

Table 3-2. Snow pack information.

Parameter	Date
Start of snow pack	Nov. 29
Start of snow melt	Jan. 30
End of snow melt	Feb. 20

Parameters representative of vegetation for the site were estimated from available information. For each scenario, the growing season ran from April 15 through October 1. Vegetation on the soil cover surface was assumed to be a poor stand of grass comparable with existing INEEL native vegetation. The hydrologic model represents the vegetative cover through the use of the leaf area index in the model and SCS curve number. The moisture limiting point and wilting point of the plants were estimated at 100 and 1500 kPa, respectively, and a rooting depth for the vegetation was estimated at 0.31 m. The curve number was determined from tables developed by the SCS. The base curve number used was 79. This represents pasture or range land with no mechanical treatment. The land is assumed to be in poor condition, which is representative of less than 50% vegetative ground cover. The silt loam soil used for the cover belongs to hydrologic soil group B. The antecedent moisture condition (AMC) was assumed to be II.

3.3 Soil Data

The material properties used in the hydrologic model are estimated representative materials to be used during construction (engineered materials) of the ICDF landfill cover. The actual hydraulic properties of the materials used during construction will be tested and the model rerun using these data at a later date. A description of each soil layer and properties are provided in the following subsections.

3.3.1 Upper and Middle Cover Sections

The upper and middle cover sections consist of a water storage layer, sand filters, and a biointrusion layer. The water storage layer consists of a 2-meter- (m)-thick fine-grained soil (silt loam) over a capillary break consisting of 0.31 m of fine sand overlying 0.31 m of coarse sand. Its function is to provide water storage and release back to the atmosphere. The upper cover section includes sand layers that provide a capillary break and are graded to prevent migration of fines into the underlying layers. Soil covers employing capillary breaks have been shown to be effective in minimizing infiltration into underlying waste in arid and semi-arid regions (Khire et al. 2000). In its most simple form, this concept consists of a fine-grained soil overlying a coarser layer. The contrast in unsaturated hydraulic properties between the layers restricts water movement across the interface of the layers. Store and release covers that incorporate a capillary break are designed to release the moisture retained in the upper, fine-grained layer through evaporative processes.

The following soil properties were determined for the water storage layer and underlying sand layers:

- Porosity
- Specific gravity
- Saturated hydraulic conductivity
- Coefficient of volume change
- Soil water characteristics curve
- Relative conductivity function (unsaturated hydraulic conductivity)
- Thermal conductivity function
- Volumetric specific heat function.

SoilVision Systems Ltd. (SoilVision) provided soil hydraulic data from its database of representative soils that have been collected from educational institutes, government organizations, and private companies. These data were selected to be representative of the soil water characteristic curve (SWCC), saturated conductivity, and porosity for a silt-loam (cover soil) and a fine and coarse sand (capillary break material) of the soils locally available at INEEL or could be engineered from local available soils. For the silt-loam SWCC, soil number 10825 was selected as a representative average of the 23 different silt-loam soils provided by SoilVision. SoilVision soil numbers 12463 and 11062 for the fine and coarse sand layers, respectively, were selected from the data set to provide a good capillary break with the silt-loam. SoilVision provided the saturated hydraulic conductivity for each of the soil numbers selected. The soils data and SWCC of the selected soil numbers are provided in Appendix C.

The middle landfill cover section consists of a layer of cobbles to prevent burrowing animals from penetrating the lower section of the cover and waste materials. The properties for the cobbles were provided by Geo-Analysis 2000, the developers of SoilCover™. Table 3-1, Soil Properties, shows the properties for each material used in the simulation.

Table 3-1. Soil properties.

Parameter	Silt Loam	Fine Sand	Coarse Sand	Cobbles
Porosity (%)	44.1	38.7	26.5	26.5
Specific gravity	2.65	2.63	2.65	2.65
Saturated hydraulic conductivity (cm/sec)	5 × 10-4	2 × 10-3	1 × 10-2	1 × 10-1

The relative permeability, thermal conductivity, and the volumetric-specific heat functions were estimated using the functions included in SoilCover™. It was assumed that the unsaturated permeability of the silt, fine sand, and coarse sand did not decrease below 1×10^{-8} centimeters per second (cm/sec) providing a conservative residual moisture content. The SWCCs and unsaturated permeability curves for each soil are shown in Appendix C.

3.3.2 Lower Cover Section

The lower cover section consists of drainage sand underlain by a flexible membrane liner (e.g., high-density polyethylene [HDPE] liner) and low permeability CCL in accordance with RCRA Subtitle requirements. Only the earthen-type materials were included in the hydrologic model. The CCL will have the equivalent permeability as the CCL used in the bottom liner system of the ICDF landfill so was assumed to have a maximum saturated hydraulic conductivity of 1×10^{-7} cm/sec. The drainage sand was assumed to be free draining and have a minimum saturated hydraulic conductivity of 1×10^{-2} cm/sec.

4. HYDROLOGIC ANALYSIS

Two-dimensional infiltration analysis of the proposed cover was conducted to account for the additional reduction in infiltration provided by surface water runoff, and lateral drainage above the compacted clay barrier layer. The cover was assumed to be sloped at a minimum of 3% after settlement (DOE-ID 2001b). The analyses were conducted for both the base case and extreme scenarios as described in Section 3.1.

4.1 Surface Water Runoff

The surface water run-off component of the model is shown as Point C in Figure 2-1. Surface water runoff was calculated using the curve number method developed by the U.S. Soil Conservation Service (SCS). The curve number method developed by the SCS uses the equation (1) given below to determine the daily runoff.

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{1}$$

Where,

Q = storm runoff in in.

P = storm rainfall in in.

S = potential maximum retention in in.

$$= \frac{1000}{CN} - 10$$

CN = curve number.

The curve number is based on soil type, land use, and AMC for the ground surface. The higher the curve number, the greater the runoff. The curve number was determined from tables developed by the SCS. The base curve number used was 79 as described in Section 3.2.

This base curve number was adjusted for the slope of the cover using the method utilized by the HELP model (EPA 1994). This method adjusts the curve number based on the slope of the surface and the length of the slope using the equation (2) below.

$$CN_a = 100 - (100 - CN)\left(\frac{L^{*2}}{S^{*2}}\right)^{CN^{-0.81}} \tag{2}$$

Where,

CN_a = adjusted curve number

CN = base curve number

L* = standardized dimensionless length (L/500 ft)

S* = standardized dimensionless slope (S/0.04).

By the SCS curve number equation, a storm event must exceed a certain amount of precipitation before runoff will begin. This initial abstraction is estimated using the equation (3):

$$I_A = 0.2\,S \tag{3}$$

Total runoff during the base case simulation period was calculated using the SCS method as 1.3 mm per year, which represents approximately 0.6% of the total annual precipitation. The runoff for the extreme case simulation was 3.33 mm per year, which is approximately 1% of the total annual precipitation. To account for the runoff in the hydrologic model, the daily precipitation values were adjusted by subtracting the runoff from the recorded precipitation. The observation point location in the model for run-off is shown at Point C in Figure 2-1. The run-off and resulting adjusted precipitation values are provided in Table D-2 and D-3 in Appendix D for the base and extreme climate scenarios, respectively.

4.2 Upper Cover Section Breakthrough

The upper cover section breakthrough component of the model is shown as Point D in Figure 2-1. The one-dimensional hydrologic model SoilCover™ 2000 was used to determine the daily flux at the base of the water storage cover layer. SoilCover™ is a one-dimensional, finite-element package that models transient flow and energy conditions within a soil section. The model uses physically based methods for predicting the exchange of water and energy between the atmosphere and a soil surface and movement of water within a soil profile. The theory is based on the well-known principles of Darcy's and Fick's Laws, which describe the flow of liquid and vapor, and Fourier's Law, which describes conductive heat flow in the soil profile below the soil-atmosphere boundary. SoilCover™ predicts the evaporative flux from a saturated or an unsaturated soil surface on the basis of site-specific atmospheric conditions, vegetative cover, and soil properties and conditions. A detailed description of SoilCover™ is provided in Appendix A.

The adjusted precipitation described in Section 4.1 was input into the SoilCover™ 2000 computer program, along with the other climatological and soil properties described in Section 3. The SoilCover™ 2000 computer program approximates run-off using a method that includes a small inherent error. Precipitation events that created run-off by the computer program were extended to eliminate run-off. Run-off amounts were calculated as described in Section 4.1.

The average annual infiltration at Point D located at the base of the water storage layer shown in Figure 2-1 for the base and extreme climatic scenario with the adjusted precipitation is given in Table 4.1.

Table 4-1. Average annual flux at base of water storage layer.

	Base Climatic Scenario	Extreme Climatic Scenario
Adjusted precipitation (mm/year)	236	335
Evapotranspiration (mm/year)	235	334
Infiltration at base of water storage layer (mm/year)	0.40	0.46

The daily infiltration amounts are provided in Tables D-2 and D-3 in Appendix D for the base and extreme climate scenarios, respectively. The computer model simulation summary sheets using the adjusted precipitation are also included at the end of Appendix D.

4.3 Infiltration Due To Biological Intrusion

Studies performed at INEEL have shown that small mammals can potentially burrow deep enough to reach waste materials. Waste can be transported upward and holes left behind can increase infiltration into the cover. Biobarrier demonstration plots at INEEL showed that 1- to 2-in. size cobbles were effective in preventing animals from borrowing to underlying soil layers (Laundre 1996).

The increase in infiltration through the upper section water storage layer from a burrow was determined assuming a mammal left a hole that could be flooded during precipitation events. It was assumed that the animal created one hole in the cover with a diameter of 20 cm that went through the upper section of the cover to the bio-intrusion layer. This hole drained an area 10 times the diameter of the hole, 200 cm. All precipitation contacting this area was added to the infiltration at Point D of Figure 2.1 as determined from the SoilCover™ model. A schematic of the defect is shown on Figure 4-1.

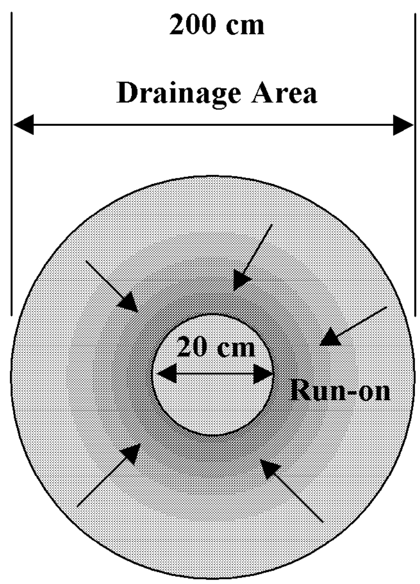

Figure 4-1. Defect Schematic.

The area drained by the burrow is given by the equation (4):

$$A_D = \frac{\pi (D_H \times 10)^2}{4} \tag{4}$$

Where,

A_D = area drained by the burrow

D_H = diameter of the burrow.

The volume of precipitation infiltrating to the waste is given by the equation (5):

$$V_I = P \times A_D \tag{5}$$

Where,

V_I = volume of infiltration

P = annual precipitation.

The annual infiltration per unit area of the landfill is given by the equation (6):

$$I_{avg} = \frac{V_I}{A} \tag{6}$$

Where,

I_{avg} = average annual infiltration

A = the area of the landfill.

The infiltration through the water storage layer resulting from bio-intrusion at Point D shown in Figure 2-1 was computed as 0.01 mm/year for the base case and 0.02 mm/year for the extreme case. The daily infiltration due to biointrusion is provided in Tables D-2 and D-3 in Appendix D for the base and extreme climate scenario, respectively.

4.4 Lateral Drainage

The lateral drainage in the lower cover section of the model is shown as Point E in Figure 2-1. Drainage from the lateral drainage layer located directly above the CCL was calculated using the Dupuit flow equation. This method assumes saturated steady-state flow and that the hydraulic gradient is equal to the slope of the cover. The Dupuit flow equation (7) is:

$$q' = -\frac{1}{2}K\left(\frac{h_2^2 - h_1^2}{L}\right) \tag{7}$$

Where,

q' = drainage from the drainage layer in flow per unit width

K = saturated hydraulic conductivity of the drainage layer

h_2 = hydraulic head at the drain = infiltration through water storage layer

h_1 = hydraulic head at the crest of the cover = L sin α + infiltration

L = horizontal length of the slope

α = slope of the cover.

Hydraulic head in the drainage layer was determined using the vertical downward infiltration at Point D shown in Figure 2-1 determined by the SoilCover™ program plus the infiltration due to bio-intrusion. The volume of water that can be removed by the drainage layer is a function of its slope, length, and permeability. For the base and extreme climate scenarios, the drainage layer can remove approximately 112 and 136 m^3/year of water given the amount of hydraulic head on the CCL. Additional hydraulic head will result in additional removal capacity of the drainage layer. The water removal capacity of the drainage layer was compared to the infiltration rate from the upper cover section to determine potential infiltration into the compacted clay and build-up of hydraulic head in the drainage layer. Spreading the volume of water that can be removed from the drainage layer over the area of the cover results in 894 and 1,094 mm/year water removal rate for the base and extreme climate scenarios, respectively. Comparing these values to the predicted infiltration from the upper cover section of 0.41 and 0.48 mm/year (including 0.01 mm/year due to defects caused by biointrusion) for the base and extreme climate scenarios, respectively indicate that drainage will exceed infiltration minimizing percolation from the base of the CCL. Computed daily values of the removal capacity are provided in Tables D-2 and D-3 in Appendix D for the base and extreme climate scenarios, respectively.

The cover interior layers will be graded to minimize the migration of fine-grained material into the drainage layers. If the lateral drainage were to clog, drainage would be reduced and infiltration would be increased through the CCL into the waste. The maximum daily head due to infiltration resulting from bio-intrusion and breakthrough from the water storage layer is less than 0.01 mm assuming daily drainage. The lateral drainage layer in the current ICDF landfill cover design is a minimum of 300-mm thick providing adequate drainage even if some clogging were to occur.

4.5 Percolation at Base of Cover

The percolation at the base of the cover in the lower cover section of the model is shown as Point F in Figure 2-1. Infiltration at this point can enter the waste mass potentially generating leachate and migration of contaminants in the waste.

More than 99.9% of the infiltration is reduced by the upper section of the cover. The lateral drainage and other porous layers in the middle and lower section of the cover will further reduce the remaining 0.1 percentage of infiltration to near zero. The small remaining fraction could infiltrate through leaks in the geomembrane and through the low permeable compacted clay in the short term. In the long term, the geomembrane may degrades, allowing infiltration directly through the low permeable CCL.

Hydrologic simulations of landfill bottom liner systems using EPA's HELP model have been performed by researchers to determine the effectiveness of bottom liner systems. Correlations between infiltration and percolation through landfill liner systems were developed to determine the minimum saturated permeability requirement of 1×10^{-7} cm/sec. These correlations also provide good estimates of the percentage of infiltration that results in percolation at the base of the liner system. For a low permeable CCL (e.g., without a geomembrane), a maximum 20% of the infiltration resulted in percolation through the CCL. The remaining 80% resulted in lateral drainage (Peyton and Schroeder 1990). Applying this relationship for the ICDF landfill cover provides a conservative estimate of percolation from the base of the CCL. The percolation at Point F shown in Figure 2-1 is shown in the equation (8):

$$Q = \text{Water Storage Layer Flux} \times 20\%/100 \quad (8)$$

Where

Water Storage Layer Flux = 0.41 mm/year for the base climate scenario and 0.48 for the extreme climate scenario including infiltration due to cover defects

so

Q_{base} = 0.41 mm/year × 0.20 = 0.08 ~ 0.1 mm/year

and

Q_{ext} = 0.48 mm/year × 0.20 = 0.09 ~ 0.1 mm/year

therefore

Q = 0.1 mm/year of percolation from the base of CCL.

Based on the above analysis, an average annual percolation rate of 0.1 mm/year is estimated to drain from the base of the ICDF landfill cover and contact the underlying waste mass. Although a small value, the average annual percolation rate of 0.1 mm/year is conservative since it would require a near steady source of infiltrating water through the landfill cover system.

5. SENSITIVITY ANALYSES

Sensitivity analyses were conducted to determine effects of changes in thickness of the silt loam layer and increased precipitation on the cover's performance. This section specifically addresses sensitivity of the cover to the variations mentioned above. Long-term cover performance issues to which these analyses also apply are addressed in other studies including the "Landfill Compaction/Subsidence Study," (DOE-ID 2001b) and the "Liner and Final Cover Long-Term Performance Evaluation and Final Cover Life Cycle Expectation," (DOE-ID 2001c).

To increase computational efficiency, the sensitivity was performed using only the upper portion of the middle section of the cover system. One-dimensional unsaturated flow conditions on a flat landfill cover surface was assumed to allow use of the SoilCover™ computer program to determine sensitivity. Observation Point D was used as the point of interest for evaluating infiltration. A summary of the sensitivity is provided below. The detailed analyses are provided in Appendix E.

5.1 Thickness Sensitivity of Water Storage Layer

Changes in thickness of the silt loam layer of the water storage section were evaluated using the base and extreme climate scenarios. The modeling methodology was the same as was used to determine the infiltration at Point D in previous models. The silt loam water storage layer thickness was varied from 0.25 to 3.5 m. The results of the computer simulations are provided in Appendix E.

At a thickness of 0.25 m, average annual infiltration was reduced to approximately 18 mm/year. Increasing the cover thickness to 0.5 m reduced the average annual infiltration to approximately 10 mm/year. A cover thickness of 1.5 m reduced infiltration to less than 2 mm/year. Average annual infiltration was less than 1 mm/year for cover thickness of 2 m and greater.

The sensitivity analysis shows clearly that increasing the water storage thickness beyond the optimal thickness does not provide added water storage. Based on the analysis, the optimal water storage layer thickness is between 1.5 and 2 m. Insignificant changes in infiltration occur for the water storage layer thickness beyond 2 m. A minimum water storage layer thickness of 2 m is recommended for the ICDF landfill cover. Additional material may be required to address erosion control and aeolian effects. A thicker water storage layer may be needed so that the minimum thickness is maintained after long term erosion. These studies are provided in the Liner and Final Cover Long-Term Performance Evaluation and Final Cover Life Cycle Expectation (DOE-ID 200c). The detailed computer model simulation summary sheets are provided in Appendix E.

5.2 Precipitation Sensitivity

The effect of increased precipitation on infiltration through the water storage layer of the cover was analyzed using an average year of weather and multiples of the average year's precipitation. The weather data for the year was repeated until the soil profile reached a quasi-steady state. The year with total precipitation closest to average was 1975, which had 269 mm of precipitation including 51 mm of water equivalent snowfall. The average precipitation for the period of record is 218 mm per year including 37 mm of water equivalent snowfall. This weather set is included in the base case scenario and included in Appendix B.

The one-dimensional computer was run using one, two, three, and four times the 1975 precipitation. Twenty years were modeled for each precipitation interval using two 10-year simulations. Initial conditions for the first simulation were the same as used for the base case simulation described in

Section 3. Final conditions from the first simulation were used as the initial conditions for the second simulation.

The quasi-steady state was determined by the change in the sum of the infiltration through the silt loam and the evapotranspiration at the end of each year modeled. When the annual change in this sum approximated the water balance error for the model, the system was determined to be in a quasi-steady state.

Based on the analysis, the upper cover may become ineffective when exposed to an average annual precipitation of greater than 810 mm/year. This also assumes all other climate parameters remain constant. The resulting infiltration at the point D layer is 0.17 mm/year at 3 times the average annual precipitation, which is less than the 0.46 mm/year infiltration based on the extreme climatological scenario.

6. RESULTS

Water movement was calculated from the cover layer represented by the observation points shown in Figure 6-1. A summary of the average annual results at each of the observation points shown in Figure 6-1 are provided in Table 6-1.

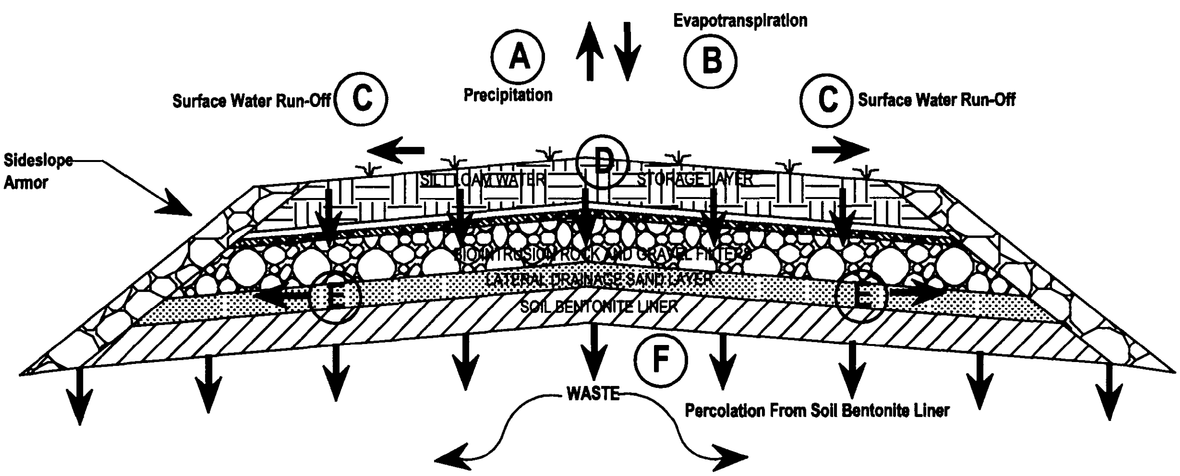

Figure 6-1. Hydrologic model geometry and location of observation points.

Table 6-1. Summary of water movement from cover layers.

		Base Case		Extreme Case	
Point	Description	Value	Direction	Value	Direction
A	Average annual precipitation (mm/year)	237	Downward	338	Downward
A	Adjusted average annual precipitation[a] (mm/year)	236	Downward	335	Downward
B	Evapotranspiration (mm/year)	235	Upward	334	Upward
C	Surface runoff (mm/year)	1.33	Lateral	3.33	Lateral
D	Bio-intrusion[b] (mm/year)	0.01	Downward	0.02	Downward
D	Water storage layer breakthrough (mm/year)	0.40	Downward	0.46	Downward
E	Lateral drainage removal capacity[c] (m^3/year)	112	Lateral	136	Lateral
F	Percolation at base of cover[d] (mm/year)	0.1	Downward	0.1	Downward

Notes:

a. Precipitation adjusted based on surface runoff.

b. Bio-intrusion includes a hole in the water storage layer caused by an borrowing animal.

c. Lateral drainage removal capacity is based on the hydraulic head determined from the upper landfill cover section infiltration rate. Greater removal capacities are possible for a larger hydraulic head.

d. Percolation at the base of cover is based on 20% of the water storage layer breakthrough.

The values listed in Table 6-1 represent average annual flow from the main components of the cover system. The flux or breakthrough from the water storage layer represented by point D is assumed to be the same at the crest and down slope areas. The difference between the flux at the crest and down slope portion of the cover is expected to be small, since surface run-off is small and the lateral movement of water within the water storage layer will be minimal, due to its low saturated permeability and gradual slope.

The silt loam water storage layer thickness was varied from 0.25 to 3.5 m to determine the optimum water storage layer thickness. The results of the sensitivity analysis indicate that the minimum recommended thickness of the silt loam layer is 2 m. Increasing the water storage layer thickness may provide additional protection for erosion and other aeolian effects, however it will not further reduce infiltration.

The effect of increased precipitation on infiltration through the water storage layer of the cover was analyzed using an average year of weather and repeating that weather scenario until the soil profile reached a quasi-steady state. The year with total precipitation closest to average was 1975, which had 269 mm of precipitation including 51 mm of water equivalent snowfall. The one-dimensional computer model was simulated one, two, three, and four times the 1975 precipitation. Twenty years were modeled for each precipitation interval using two 10-year simulations to determine the quasi-steady state. Based on the analysis, the upper cover section remains effective to three times the average annual precipitation, which is 810 mm/year. The resulting infiltration at Point D is 0.17 mm/year, which is less than the actual infiltration 0.49 mm/year determined in Section 4.2. Precipitation of four times the average annual precipitation saturates the water storage layer rendering it ineffective for reducing infiltration.

7. SUMMARY AND CONCLUSIONS

The current hydrologic landfill cover model showed that the upper and middle landfill cover sections alone for a flat surface were effective in reducing the infiltration using conservative estimates of long-term base and extreme cases of climatological conditions to less than 0.4 and 0.5 mm average annual infiltration, respectively (DOE-ID 2001a). The results of this study show that infiltration is further reduced by surface run-off and lateral drainage to less than 0.1 mm per year at the base of the cover system including defects in the cover.

Two climatic scenarios were used for the analyses. The base scenario consisted of a 10-year period with an average annual precipitation near the long-term average for the site. The extreme scenario included the four years with precipitation above the 90th percentile value. The weather data used were provided by INEEL and covered the years 1950 through 1994. Weather data for 1995 was supplied by NOAA from data collected at the INEEL site. The soil data used for the silt loam cover material and the fine and coarse sands of the capillary break came from Soil Vision, Ltd. and included saturated hydraulic conductivity, porosity, and a soil water characteristic curve. The soil properties for the cobbles were provided by Geo-Analysis 2000 Ltd. The material properties used in the simulations are representative of materials that may be found near the site and will be used during construction of the ICDF landfill cover. The actual hydraulic properties of the materials used during construction will be tested and the model rerun with these data at a later date.

The results of the analyses indicate 0.1 mm/year of infiltration through the lower section of the soil cover into the waste. This is considered reasonably conservative for the reasons listed below:

- All snow was assumed to melt in a 22-day period each year stressing the cover's water storage capacity.
- The unsaturated permeability of the silt-loam, fine sand, and coarse sand was not allowed to go below 1×10^{-8} centimeters per second (cm/sec) providing a conservative residual moisture, essentially, not allowing the cover to reach a very dry condition and provide additional water storage.
- A poor stand of grass was assumed to simulate drought or post-fire conditions.
- The daily precipitation was distributed over 12 hours increasing infiltration into the cover.
- The years selected for the weather data included large precipitation events early on in the simulation to stress the recovery capacity of the cover.
- An extreme case was modeled that assumed four years of back-to-back precipitation events that were above the 90th percentile based on the period of record.
- Bio-intrusion does not account for increased evaporation from lower depths of the soil resulting from increased air circulation or for evaporation and dispersion resulting from precipitation moving through the soil.

The sensitivity results show that the cover will perform as modeled for precipitation up to three times the annual average. Increasing the water storage layer thickness greater than 2 m results in minimal improvement in hydraulic performance.

The results presented for infiltration through the ICDF landfill cover are consistent with results from other studies of comparable cover systems under similar climatic conditions. Previous studies have been conducted to evaluate the moisture movement in engineered barriers at the INEEL (Magnuson 1993). One of the barriers evaluated by Magnuson included a 1.5-m soil cover over a gravel (0.15 m) and cobble (0.76 m) capillary break. This cover design is similar to that proposed for the ICDF landfill, in that it was designed as a store and release cover over a capillary break. Simulations indicated that drainage through the upper soil layer for this cover was extremely low, on the order of the mass balance error of the simulations (Magnuson 1993). Drainage through the soil layer was believed to be associated with drainage of the initial moisture in the profile.

Engineered barriers of two designs are being tested at the Engineered Barriers Test Facility (EBTF) at INEEL. The first design consists of a thick, vegetated soil cover. The second design incorporates a capillary/bio-barrier within the soil cover. Each test plot is instrumented to monitor soil-water movement within the barrier profile. Wetting tests were designed to stress the test plots to conditions that resulted in drainage and to monitor the recovery of the systems under ambient conditions. Results from these studies are reported in Porro and Keck (1998) and Porro (2000).

Recovery of the capillary barrier to breakthrough from infiltration was evaluated by Porro (2000). The capillary barrier was similar in design to that evaluated in the simulations conducted by Magnuson (1993) (i.e., a 1.45 m silt loam soil over 0.15 m gravel and 0.76 m cobble). Neither test plot (thick soil or soil with a capillary break) produced drainage as a result of exposure to ambient conditions, however the internal distribution of water within the plots indicated that the capillary barrier was more effective in limiting the downward movement of water. Both test plots were irrigated to induce breakthrough in 1997. As a result, infiltration of melting snow the following spring produced drainage in all plots. The drainage through the capillary barrier was less in total volume than drainage from the thick soil cover. Evaporation alone (without transpiration) was sufficient to restore the functioning capacity of the capillary barrier within two years following the intentionally induced breakthrough events. These results are consistent with studies conducted by Anderson et al. (1997) as part of the Protective Cap/Biobarrier Experiment at the INEEL Experimental Field Station, which indicated that ambient precipitation and supplemental irrigation treatments did not produce drainage through 2 m soil profiles.

Capillary barriers have also been evaluated at other sites for inclusion in landfill cover systems, especially for sites in the western United States where potential evaporation tends to exceed precipitation. At the DOE Hanford Site, a field-scale prototype surface barrier was constructed in 1994 over an existing waste site (Gee et al. 1997). This barrier was subjected to three times the annual average precipitation for two consecutive years including one storm event representing the 1,000-year return storm, which was applied in March when soil-water storage was at a maximum. The 2.0 m silt-loam soil cover has not drained in response to these stresses. Capillary barriers have also been evaluated using computer simulations for climatic conditions indicative of the arid western U.S. (i.e., Salt Lake City, Utah, and Albuquerque, New Mexico). These studies have found that the barriers are effective in producing no drainage during 10-year simulations that included a 5-year period with the highest recorded precipitation rates (Morris and Stormont 1997).

Based on the results from the simulations reported in this EDF for the ICDF landfill cover, results from experimental studies at the INEEL, and experimental and modeling results from other sites in the western U.S., it is believed that the cover design proposed for the ICDF landfill represents a state-of-the-practice design for a landfill cover that minimizes infiltration into the waste. Any leakage that occurs through the cover is likely to be intercepted by the lateral drainage layers at the base of the cover. A conservative estimate of 0.1 mm/year of percolation from the base of the cover was determined based on the estimated breakthrough from the upper section of the cover. Based on the results reported in this EDF, it is believed that the cover design, which incorporates a store and release soil cover underlain by a capillary break and composite liner system, represents the best technology for minimizing infiltration into the landfill given site-specific climatic conditions.

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